

# Juno Gravity Science: Preparing for Data Collection at Jupiter

Dustin Buccino

(818) 393 – 1072

Dustin.R.Buccino@jpl.nasa.gov

Daniel Kahan

(818) 393 – 2803

Daniel.S.Kahan@jpl.nasa.gov

Kamal Oudrihri

(818) 393 – 1143

Kamal.Oudrihri@jpl.nasa.gov

Oscar Yang

(818) 354 – 5747

Oscar.Yang@jpl.nasa.gov

Jet Propulsion Laboratory, California Institute of Technology

4800 Oak Grove Dr.

Radio Science Systems Group

Pasadena, CA 91109

**Abstract**—One of the primary goals of the Juno mission is to investigate Jupiter’s interior by mapping its gravitational field with the gravity science instrument. The Juno spacecraft has two radio science components that comprise the gravity science instrument: the X-band telecommunications system for a X-up/X-down link and a Ka-band Translator for a Ka-up/Ka-down link. The Deep Space Network’s DSS-25 beam waveguide antenna at the Goldstone Deep Space Communications Complex in California provides the X- and Ka-band uplink alongside an Advanced Water Vapor Radiometer to calibrate tropospheric effects. X-band and Ka-band downlink data are collected with both open-loop and closed-loop receivers located at the complex. Utilization of Ka-band provides scientific benefit to the Doppler measurements, but also adds operational challenges. Pointing of the uplink and downlink Ka-band signals requires additional systems to be calibrated and operated by the Deep Space Network; and the higher frequency of Ka-band means the signal dynamics are increased by a factor of four over X-band signals. Due to the spacecraft’s elliptical orbit and 4000 kilometer perijove altitude, it accelerates at an extreme rate as it approaches Jupiter, inducing large dynamic ranges in Doppler range of approximately 6 MHz over 3 hours at Ka-band. After the installation of a new Ka-band transmitter at DSS-25 for Juno was completed in 2015, end-to-end testing was conducted to ensure readiness for operations at Jupiter and provide an initial assessment of the performance. Cruise testing was conducted in the same operational configuration that the system will be used in during perijove passes. Processed open-loop data yielded uncalibrated Doppler residuals of 1.9 mHz at X-band and 6.0 mHz at Ka-band with 5-second compression time. Conduction of these tests has prepared the instrument and the operations team for science data collection during the science phase of the mission.

## TABLE OF CONTENTS

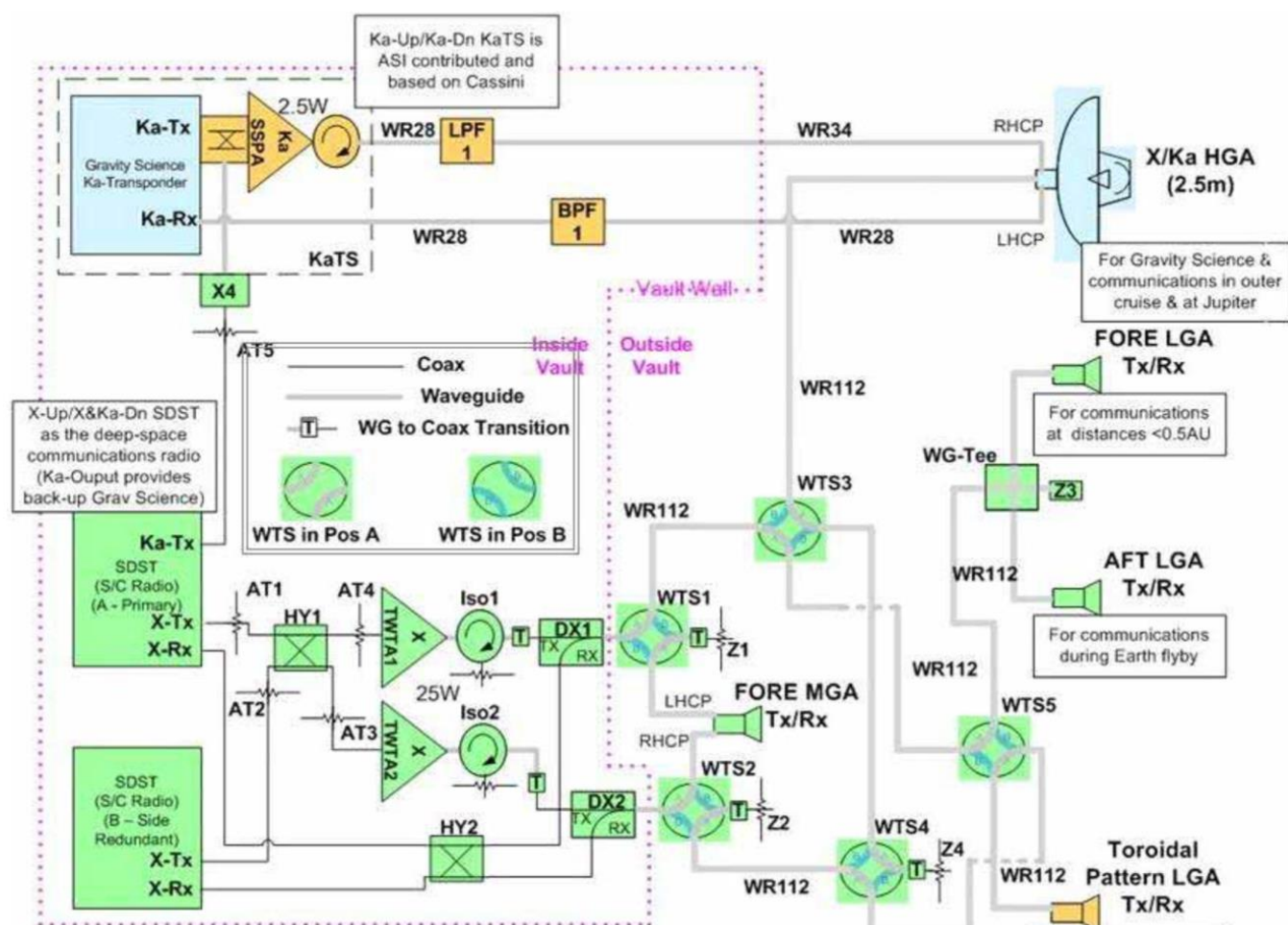
1. INTRODUCTION .....	1
2. INSTRUMENT OVERVIEW.....	2
3. JUPITER SCIENCE OPERATIONS CONCEPT.....	3
4. CRUISE TEST RESULTS .....	5
5. RECENT ACTIVITIES .....	6
6. UPCOMING ACTIVITIES .....	8
7. CONCLUSION .....	8

## 1. INTRODUCTION

Juno is a National Aeronautics and Space Administration (NASA) New Frontiers mission with goals to learn about Jupiter’s origin. The spacecraft, launched on August 5, 2011, spent five years in interplanetary cruise. After leaving Earth, the spacecraft performed two deep space maneuvers, targeting an Earth flyby in 2013. On July 4, 2016, the spacecraft executed an orbit insertion burn placing it in a 53.5-day, highly elliptical polar capture orbit. After two of these orbits, it was planned to execute a period reduction maneuver in October 2016 in order to reduce the period to 14-days. However, due to an anomaly in the propulsion system, the maneuver was cancelled until more information can be gathered on the cause of the anomaly. If Juno remains in 53-day orbits, solar eclipse will occur in late 2019 as the orbit plane rotates around the planet with respect to the sun.

Juno’s primary science investigations focus on five areas: atmospheric composition, atmospheric structure, magnetic field, gravity field, and polar magnetosphere. A suite of eight science instruments provides the measurements to evaluate these characteristics of Jupiter. The gravity science investigation will determine the gravity field to constrain the mass of the core, probe the centrifugal response of the planet to investigate the deep zonal flow, and investigate the tidal response from Io. To investigate the interior, the gravity science investigation utilizes the X-band telecommunications link and Ka-band Radio Science link between the spacecraft and Earth-based observing stations of NASA’s Deep Space Network (DSN) to measure the Doppler shift caused by the motion of the spacecraft. As the spacecraft flies close to Jupiter during perijove, the signals become sensitive to the changes in the gravitational field.

The Juno gravity science Engineering Team (referred to as simply the engineering team or the instrument operations team) operates the gravity science instrument. The engineering team is located at the Jet Propulsion Laboratory in the Radio Science Systems Group. The Juno gravity science Engineering Team is the operational interface between the Juno gravity science investigators, the Juno project, and the DSN. Engineering support is separated into uplink processes, which include science planning, DSN scheduling, and spacecraft sequencing, and downlink processes, which include data collection, processing, analysis, distribution, and archiving.



science. The key components of the telecom subsystem include:

**Small Deep Space Transponder (SDST):** There are two distinct SDSTs. The prime unit has the capability to provide X-up/X-down and X-up/Ka-down (X-band/Ka-band provided as a backup to the KaT) while the redundant unit has only a single band X-up/X-down. Four different modules make up the SDST: the digital processing module (DPM), the downconverter module, the power converter module, and the exciter module. The X-band downlink carrier (8404 MHz) is generated by the SDST by coherently multiplying the frequency of the uplink carrier (7153 MHz) by the turn-around ratio 880/749.

**Traveling Wave Tube Amplifier (TWTA):** There are two redundant 25 Watt X-Band TWTA's on Juno. The TWTA is comprised of the traveling wave tube and the electronic power converter.

**High-Gain Antenna (HGA):** The HGA is a 2.5-m dual-band (X and Ka) dual reflector. All nominal X- and Ka-band gravity passes use the HGA.

**The Ka-band Translator (KaT)**—The Ka-band translator is a radio science instrument that is used for Doppler tracking at Jupiter. It receives a Ka-band uplink carrier at 34 GHz and down converts it to the downlink carrier at 32 GHz. The KaT design is based on an advanced signal processing algorithm to enable optimization of carrier acquisition and tracking [6].

#### Ground System

The Deep Space Network is a system of antennas used for commanding, tracking, and monitoring about 35 interplanetary missions flown by NASA and other international space agencies. Three complexes, spaced evenly around the Earth at Goldstone, California; Madrid, Spain; and Canberra, Australia provide continuous coverage for these spacecraft as the Earth rotates. Each complex includes one 70-m dish and several 34-m antennas.

Among the 34-m antennas, the beam waveguide (BWG) antennas are the newest and most sophisticated. Namely, the BWGs have a series of mirrors that reflect radio signals from the antenna to a room below the ground. With their highly sensitive electronics housed safely underground, these antennas can be maintained more easily and can be modified more readily for new technologies. For example, the BWGs are capable of the simultaneous X-Band and Ka-Band reception needed for Juno gravity science [2].

One of the beam waveguide antennas, Deep Space Station 25 (DSS-25), had a new Ka-Band transmitter installed in 2015, making it the only station capable of transmitting two different bands, X-band and Ka-band, at the same time. The original klystron-based Ka-band transmitter at DSS-25, originally built for the Cassini mission, failed twice in 2011 and 2013. A replacement was approved in 2013 and completed in 2015 for use by Juno. The transmitter has a power output of 300 W [2].

In addition, an Advanced Water Vapor Radiometer (AWVR) is located adjacent to DSS-25. The AWVR points along parallel to DSS-25 to the same position in the sky and takes

measurements of atmospheric water vapor. These measurements are used to calibrate atmospheric effects which delay the transmission of the signal as it passes through the Earth's troposphere.

When the DSN transmits to Juno or any spacecraft, the frequency of the signal is shifted, due to the Doppler effect caused by the motion of the spacecraft relative to the antenna. In order for the spacecraft to lock onto the uplink, ramps in frequency are applied to the uplink to compensate for the Doppler shift, resulting in a more stable frequency being received by the spacecraft. Similarly, the Doppler shift is applied via frequency “predicts” in the ground receivers to tune to the frequency of the signal expected on the ground. Tuning of the uplink and downlink in this fashion normalizes the frequency data collected and used for gravity science.

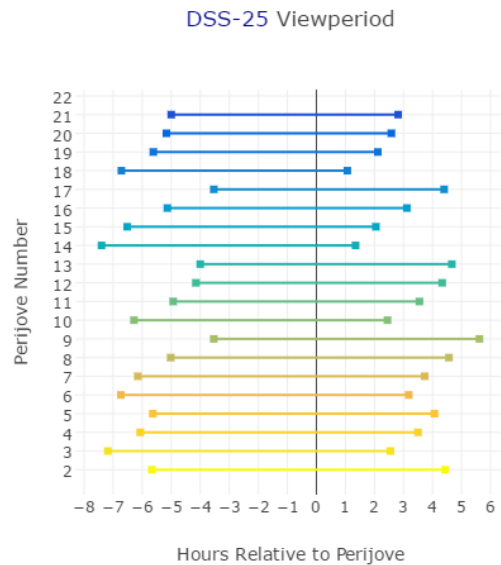
### 3. JUPITER SCIENCE OPERATIONS CONCEPT

Operating the Juno gravity science instrument is similar to other missions which have radio science components. The process begins by defining radio science activities within the constraints of the mission, including which bands are to be active and when. Next, activities are conducted in real-time operations in coordination with the project and the DSN. Finally, data are processed, analyzed, and distributed to the gravity science team for scientific analysis.

#### Science Planning

Science planning is the process of creating activity plans within the constraints of the mission, which include but are not limited to spacecraft trajectory, spacecraft power, and available DSN assets.

Because Ka-band uplink capabilities exist only at DSS-25, the mission was designed around perijoves occurring within the



**Fig. 2. Viewperiod of DSS-25 with respect to the 53-day orbit perijove number.**

visibility of that antenna. The trajectory is optimized to provide DSS-25 coverage during each science perijove, and orbit trim maneuvers are performed to keep the spacecraft on-path. Fig. 2 shows the view period of DSS-25 with respect to the science perijoves.

The Juno spacecraft has two primary orientations, an Earth-pointed attitude referred to as *GRAV* (for gravity science pointing) and a nadir-pointed attitude referred to as *MWR* (for the microwave radiometer instrument pointing). For *GRAV* perijoves, the full X/X and Ka/Ka links are used throughout the duration of the view period. A 30-minute warm-up period for the KaTS is added for thermal stabilization of the hardware. For *MWR* perijoves, only the X/X link can be utilized through the Medium Gain Antenna (MGA) due to the offset in pointing.

The engineering team provides these desired times of radio science activities to the project in order to enable the KaTS when desired and schedule the appropriate DSN assets (frequently DSS-25). The spacecraft telecom team operates the SDST for X-band. The KaTS operations is controlled by the background sequence onboard the spacecraft, generated by the mission sequencing team.

Additionally, monthly Ka-band tracking passes were scheduled prior to the period reduction maneuver in order for the DSN and the engineering team to become familiar with the procedures in the operations of the Ka-band transmitter.

### Signal Dynamics

Juno's unique, highly elliptical orbit comes within 4000 km of the massive planet's surface during perijove (radius of  $\sim 1.05R_J$ ). In combination with the need to use DSS-25, the

dynamics caused by this orbit add unique constraints to the operations.

Juno arrives at Jupiter with its orbit plane nearly perpendicular to the Jupiter-Earth direction. Due to the oblateness of the planet, the orbital plane rotates by approximately 4 degrees per orbit with respect to the Jupiter-Sun direction to become more edge-on. As shown in Fig. 3, this induces larger one-way Doppler range and rates in the received signal as the mission progresses.

The uplink is compensated for the one-way Doppler by tuning the exciter to the Doppler profile expected for the pass (both the X-band and Ka-band transmitters are Doppler compensated). Because the Ka-band transmitter had not been tested for the Doppler range and rate expected at perijove, a test was scheduled in late 2015. The test verified that the exciter is able to tune to the expected ranges at the expected rates. Additionally, the narrow beamwidth of the Ka-band signal out of the 34-m antenna requires the uplink beam to be pointed ahead of the downlink beam using an aberration correction. The aberration angle is a function of the spacecraft velocity with respect to the antenna and experiences similar high ranges and rates. This system was also tested and verified to be within the limits for the expected dynamics at perijove.

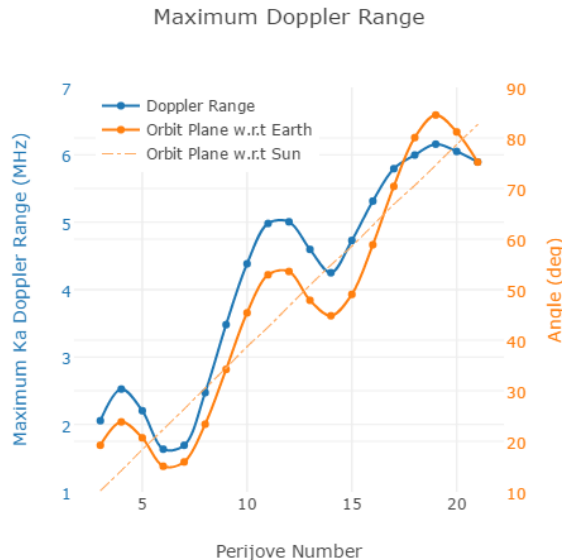
On the downlink side, the closed-loop receiver must retain lock during perijove tracks in order to acquire telemetry (for X-band), Doppler data (at X- and Ka-band), radiometric ranging data (at X-band), and in order to use the monopulse closed-loop pointing system. The monopulse pointing system compares the phase and gain of two Ka-band downlink channels to determine corrections to the antenna pointing to best point to the downlink signal [3]. The closed-loop receiver utilizes a phase-locked loop to track the downlink signal and requires a higher carrier loop bandwidth value set to maintain lock. Open-loop data contain a recording of the entire spectrum around a given downlink predict, and may be Doppler compensated to the expected dynamics such that only the error is observed.

### Engineering Support

**Real-Time Operations**—Although the commands to turn on the KaTS onboard the spacecraft are generated 4-6 weeks in advance of a Ka-band perijove pass, the data are collected on the ground at the DSS-25 antenna in near real-time.

Five days prior to the activity, the DSN releases uplink and downlink frequency predictions. The Ka-band uplink frequency predicts (referred to as “ramps”) guide the exciter on the Ka-band transmitter. These uplink ramps are modified by the engineering team to include a second acquisition sweep which will automatically execute approximately one hour after the initial acquisition sweep. The purpose of the second sweep is to ensure that the KaTS locks on to the uplink signal for the closest approach period. Due to round-trip light-times of 80-110 minutes, if the spacecraft does not lock onto the first acquisition sweep, Ka-band data at perijove may be lost.

Each track begins with a dedicated setup time where the DSN configures and calibrates the uplink and downlink systems, typically two hours in duration when Ka-band is included.



**Fig. 3. Maximum 1-Way Ka-band Doppler Range as a function of perijove number. Also shown is the orbit plane angle with respect to the direction to Earth and the Sun. The maximum dynamic range of approximately 6 MHz occurs on PJ-19.**



Once the setup period is finished, the antennas begin tracking the spacecraft. Five minutes after tracking begins, the X- and Ka-band transmitters are turned on.

The monopulse closed-loop pointing system requires periodic calibrations using a spacecraft signal to determine the phase value  $TAU$ . To conduct this calibration, the antenna is commanded off point by a few millidegrees and the monopulse system generates a correction. The error between the monopulse correction and the commanded off-point angle determines the phase value  $TAU$  [3]. Nominally, the monopulse system is calibrated during dedicated tracks with a Ka-band downlink signal. Due to the cadence of Juno's orbit and the fact that Juno's 1-Way Ka-down and 2-Way Ka-up/Ka-down frequencies are similar, monopulse calibrations are conducted in 1-Way mode during each perijove track between the first and second sweeps.

A round-trip light-time after the transmitters are turned on, the station will re-acquire the signal in two-way coherent mode. The two-way coherent data, X-up/X-down and Ka-up/Ka-down, provide the prime science data.

Throughout the data collection process, the gravity science engineering team coordinates operations with the DSN and the Juno project in order to verify correct configuration of the X- and Ka-band systems at DSS-25, with special focus on the monopulse closed-loop pointing system and Ka-band transmitter. Any issue discovered in the configuration or operations is documented and attempted to be resolved in real-time by the DSN. The open-loop receivers (RSR and WVSr) are operated by the engineering team and provide real-time insight into the signal characteristics of the downlink. Open-loop data are recorded for post-processing.

*Engineering Analysis*—The Juno gravity science engineering team's deliverables are summarized in Table 1. The engineering team processes and verifies collected open-loop data (raw spectrum I-Q values) to obtain frequency observables

**Table 1. File types delivered for gravity analysis. The primary data are ODF (TRK 2-18, from closed-loop), OLF (TRK 2-18, from open-loop), and AMC (from Advanced Water Vapor Radiometer).**

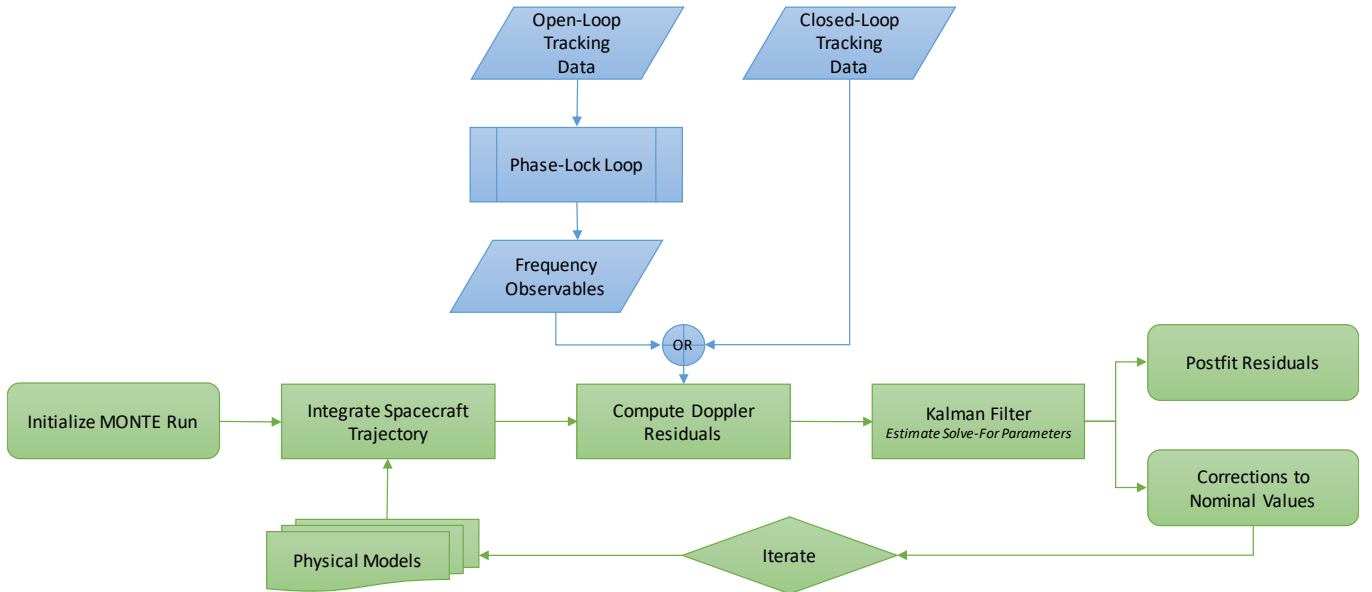
Data File	Abbv.	Purpose
Orbit Data File	ODF	Doppler/Range observables
Tracking & Nav File	TNF	Phase/Doppler/Range observables
Radio Science Data	RSR	Raw spectrum (I-Q values)
Processed RSR Data	OLF	Open-loop Doppler observables
AWVR Path Delay	AMC	Zenith path delay from AMC system
Ionosphere Calib.	ION	Earth Ionosphere calibration
Troposphere Calib.	TRO	Earth Troposphere calibration
DSN Weather File	WEA	Surface meteorology at station
Small Forces File	SFF	Spacecraft maneuver data

for the gravity science team. Frequency observables are estimated from open-loop data utilizing a phase-locked loop with a nominal carrier loop bandwidth of 1 Hz. In addition, the gravity science requires all necessary files to calibrate the Doppler frequency observables for their gravity field estimations and error analysis.

The primary data utilized are Orbit Data Files (ODF) and Open Loop Files (OLF), containing the frequency observables in the DSN standard TRK 2-18 binary format from the closed-loop and open-loop receivers, respectively. The dual X-band and Ka-band can be combined to cancel charged particle effects. Troposphere error is calibrated utilizing the Advanced Media Calibration (AMC) file, which includes path delay measured by the Advanced Water Vapor Radiometer. Secondary ancillary data are also archived for diagnostic purposes.

#### 4. CRUISE TEST RESULTS

To prepare for operations at Jupiter, tests were conducted



**Fig. 4. Data processing flowchart for cruise test results.**

**Table 2. Doppler residual performance of the X/X and Ka/Ka links during initial cruise testing in the first half of 2015.**

DOY	TLM Rate	SEP Angle	Open Loop Freq RMS (mHz)		Closed Loop Freq RMS (mHz)	
			X/X	Ka/Ka	X/X	Ka/Ka
056	30k	174°	1.28	4.44	2.19	4.48
064	50k	166°	1.32	4.24	1.91	4.48
071	50k	158°	1.57	5.35	2.24	5.34
103	50k	123°	3.35	9.80	3.59	9.61
124	30k	102°	1.96	6.14	2.80	6.19

starting in February 2015 to exercise the full DSN configuration that will be used in orbital operations at DSS-25. Initial testing primarily involved the Ka-band transmitter, and follow-up testing was conducted to ensure operations readiness of the DSN operators and the gravity science engineering team. The X-band telemetry rates were varied, using both subcarrier modulation and direct carrier modulation, to determine the performance of the X-band Doppler at various telemetry rates.

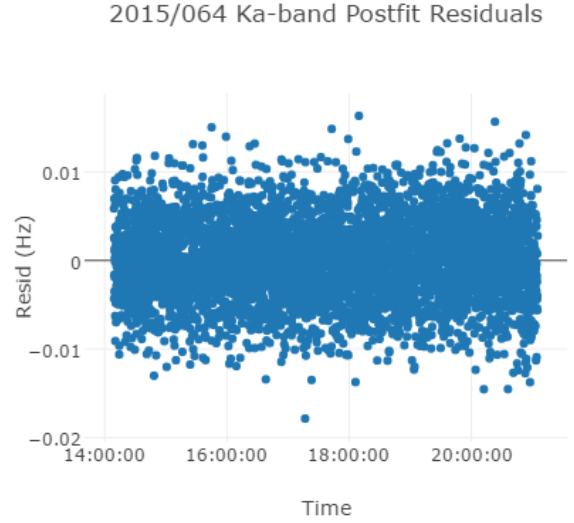
Analysis was conducted on both closed-loop and open-loop Doppler at X- and Ka-bands to determine performance. Fig. 4 shows a flowchart of the data processing technique. The Radio Science Systems Group’s Radio Science Visualization and Processing (RSVP) toolbox was utilized to extract frequency observables from the open-loop data. RSVP extracts frequency estimates from the IQ samples using a phase-locked loop with a carrier loop bandwidth set to 1 Hz. The frequency observables are processed in JPL’s Mission-analysis, Operations, and Navigation Toolkit Environment (MONTE) software to determine noise levels. MONTE processes the frequency estimates using a current-state Kalman filter to estimate the solve-for parameters. For this estimation in cruise, only the spacecraft state (position, velocity) is solved for. The root mean square of the post-fit frequency residuals provides the metric of performance.

Performance is summarized in Table 2 for each pass conducted in the first half of 2015. Sample post-fit residuals are shown in Fig. 5. The RMS of the residuals is of good quality and within requirements. It is seen that the RMS of the X-band residuals are not a function of the telemetry rate, allowing for higher data rates to be used during science perijove passes without impacting the quality of X-band gravity science data. X-band open-loop data has lower RMS than the closed-loop data, primarily due to the closed-loop carrier loop bandwidth of 8 Hz versus the 1 Hz loop bandwidth used by RSVP. It is noted that on DOY 103, the RMS of the frequency residuals are higher across the board. This is due to a more active troposphere than the rest of the passes, which can be corrected with data from the AWVR.

## 5. RECENT ACTIVITIES

### *Jupiter Orbit Insertion*

Juno fired its main engine on July 4, 2016 PDT (July 5 UTC) to enter orbit around Jupiter. In order to use the main engine in the optimal burn direction, the spacecraft was required to turn

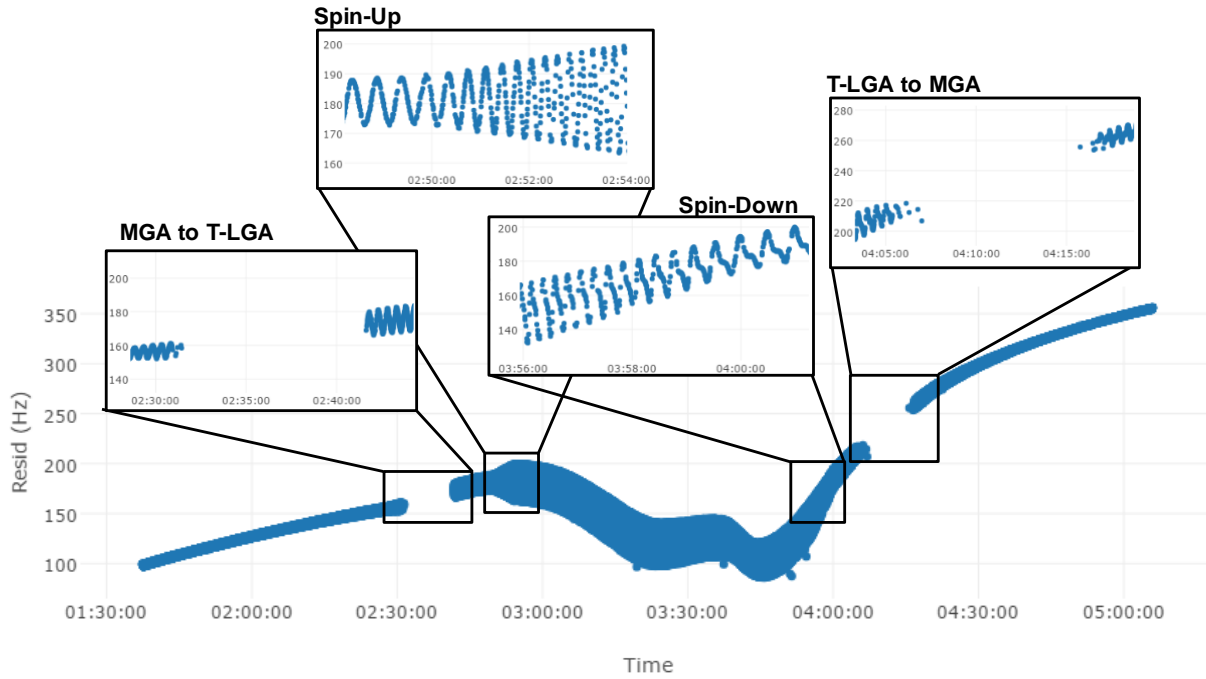


**Fig. 5. Sample Ka-up/Ka-down postfit residuals from the open-loop receiver at 5-sec count time from the 2015/064 test pass. The RMS is 4.24 mHz.**

off Earth-point. Communications were only possible using a Toroidal Low-Gain Antenna (TLGA). The Signal-to-Noise ratio on the antenna was not high enough for telemetry modulation, so instead a tones technique, similar to the Mars Science Laboratory’s Entry, Descent, and Landing communications [4], was used to send back basic messages on the status of the spacecraft. A subcarrier is modulated onto the carrier. Messages are sent by changing the frequency of the subcarrier which is detected by the ground.

Although not strictly a gravity science activity, the Juno gravity science engineering team utilized the open-loop receivers for real-time tone detection and recording. Because the signal during this time was non-coherent and the spacecraft was firing the main engine and thrusters, the data collected during JOI are not useful for the gravity investigation.

Fig. 6 shows a plot of the residual frequency around the main engine burn (approximately July 5, 2016, 01:37 to 05:06 UTC). The maneuver was included in the predicted frequency, and the overall drift in frequency is primarily due to instability in the spacecraft oscillator. Key events are highlighted on the plot. At 02:34, the spacecraft turned to the optimal burn direction and switched to utilizing the TLGA antenna. In the residual frequency, the amplitude of oscillation increases due to the antenna switch. At 02:56, the spacecraft increased its spin rate from 2 RPM to 5 RPM. The residual frequency periodicity increases in frequency and amplitude corresponding to this spin rate increase. The main engine burn itself is not clearly seen because it is included in the modeled frequency. At 03:55, the spacecraft reduced its spin rate from 5 RPM back to 2 RPM, and at 04:06 the spacecraft changed to a sun-point attitude to recharge the batteries and returned to the MGA. The corresponding changes in frequency were observed as noted in the figure.



**Fig. 7. Frequency residuals observed during JOI by the Radio Science Receiver. The predicted frequency takes into account the main engine burn, but not the spin signatures due to spacecraft rotation.**

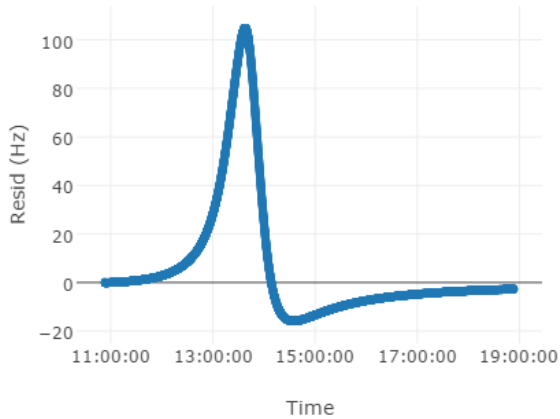
#### *Perijove #01*

Juno's first perijove pass occurred on August 27, 2016. This perijove occurred between the first two orbits in the GRAV orientation (Earth-point). The Madrid complex of the DSN supported radio science and telemetry downlink (due to the capture orbit period, the perijove was not able to be covered by the Goldstone complex). Because no Ka-band uplink is

available at Madrid, the spacecraft was sequenced using the SDST-Ka band exciter for an X-up/X-down and X-up/Ka-down configuration. Perijove occurred at 13:44 UTC Earth Receive Time.

All radio science data were collected as planned. The residual frequency (recorded value, or prefit) maximized at approximately 100 Hz in Ka-band shortly after closest approach, shown in Fig. 7, within the narrowest bandwidth of 1 kHz on the WVSr. The remaining residual is primarily error in the predicted trajectory; however, signatures due to gravitational field and pole of Jupiter are also present.

#### PJ-01 Ka-band Prefit Residual



**Fig. 6. X-up/Ka-down prefit residuals during PJ-01 over DSS-55. A majority of the residual is due to trajectory, but the gravity signature due to Jupiter's gravitational field is also present.**

#### *Perijove #02*

Since successfully entering into orbit and collecting science data during PJ-01, it was originally planned to conduct the Period Reduction Maneuver (PRM) during the second perijove on October 19, 2016 to reduce the orbital period from 53.5-days to 14-days. An anomaly in the propulsion system was detected just prior to PRM, the maneuver was cancelled. Investigation into the cause is ongoing. If deemed safe to the spacecraft, a PRM may be performed in the future to reduce the orbital period.

In place of PRM, a contingency sequence was activated onboard the spacecraft to conduct a science perijove pass in place of the maneuver. The sequence enabled Ka-band onboard the spacecraft, for a dual X- & Ka-band link over DSS-25 around perijove. Approximately 13 hours prior to perijove, the spacecraft entered safe mode, and no Ka-band Doppler data were acquired during perijove. However, coherent X-band data were collected around perijove using the SDST which can be used for gravity field determination.

### Perijove #03

The third perijove, PJ-03, occurred on December 11, 2016, in the GRAV orientation over DSS-25. This was the first use of dual X- & Ka-band links for gravity science estimation. The AWVR was running concurrently alongside the Doppler data collection to calibrate troposphere effects. This event was the first successful collection using the full configuration of the gravity science instrument and provides high quality data for the gravity science investigation.

## 6. UPCOMING ACTIVITIES

Without a PRM, science perijoves will continue in the 53-day orbit period. The next orbit, PJ-04, will be conducted on February 3, 2016, in the MWR orientation. In the MWR orientation, coherent Doppler data will be collected over DSS-25 using an X-band link through the MGA. Future science orbits will be conducted in either the MWR orientation or GRAV orientation, subject to discussions among the science team. During MWR orientations, gravity science will collect X-band Doppler data through either the MGA. In later stages of the 53-day orbit, the Low Gain Antenna (LGA) or Toroidal Low Gain Antenna (T-LGA) may be required in place of the MGA, depending on the magnitude of the Boresight-Off-Earth angle (a function of angle between the orbit plane and Earth direction).

## 7. CONCLUSION

Throughout cruise and the initial perijove passes, the Juno gravity science engineering team successfully planned, sequenced, and executed the required activities in support of instrument testing, readiness, and science data acquisition. During cruise, the Ka-band transmitter at DSS-25 and the spacecraft KaTS were successfully utilized to collect simultaneous X-up/X-down, Ka-up/Ka-down radio science Doppler data. Experiences with the Ka-band transmitter during cruise provide not only an assessment of the performance, but invaluable experience in operating the gravity science instrument system as a whole. For JOI on July 4, 2016, the engineering team supported the main engine burn through open-loop recordings and processing of tones data, providing an indication of spacecraft performance during the maneuver. In addition, this provided the team with experience with the spacecraft configured on the MGA, which will be utilized during MWR perijoves. First experiences with Ka-band during perijove were conducted during the first science perijove on August 27, 2016. The operational experiences acquired during the activities described in this paper have prepared the team for the science phase, where the first perijove tracks using the Ka-band transmitter at DSS-25 will be executed.

## ACKNOWLEDGMENT

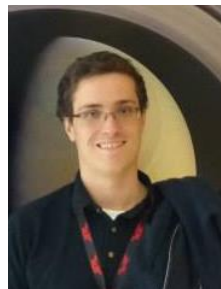
The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors would like to thank Bill Folkner, the Juno gravity science lead Co-Investigator.

## REFERENCES

- [1] Mukai, Ryan, Hansen, David, Mittskus, Anthony, Taylor, Jim, and Monika Danos. *Juno Telecommunications*. Vol. 16. Pasadena: Jet Propulsion Laboratory, 2012. DESCANSO Design and Performance Summary Series.
- [2] *DSN Telecommunications Link Design Handbook*, DSN No. 810-005, Rev. F, Jet Propulsion Laboratory, Pasadena, CA. <http://deepspace.jpl.nasa.gov/dsndocs/810-005/>
- [3] Buum Chau, Calvo, Jesus, Cheng, Tsan-Huei, and Manuel Vazquez, *Ka-band Monopulse Antenna Pointing Calibration Using Wideband Radio Sources*. IPN Progress Report 42-182, pp. 1-4, August 15, 2010. [http://ipnpr.jpl.nasa.gov/progress\\_report/42-182/182A.pdf](http://ipnpr.jpl.nasa.gov/progress_report/42-182/182A.pdf)
- [4] Oudrhiri, Kamal, et. al. *Sleuthing The MSL EDL Performance From An X Band Carrier Perspective*. 2013 IEEE Aerospace Conference. IEEE, 2013.
- [5] Bertotti, B., Comoretto, G., and Iess, L.: 1993, *Astron. Astrophys.* 269, 608.
- [6] Ciarcia, S., Simone, L., Gelfusa, D., Colucci, P., De Angelis, G., Argentieri, F., Iess, L., and R. Formaro. *MORE and Juno Ka-band Transponder Design, Performance, Qualification, and In-Flight Validation*. 6<sup>th</sup> ESA International Workshop on Tracking, Telemetry, and Command Systems for Space Applications. ESA, 2013.

## BIOGRAPHY



**Dustin Buccino** is a member of the Radio Science Systems Group at NASA's Jet Propulsion Lab. Since joining the group in 2013, he has provided scientific and engineering support to the Cassini, Dawn, InSight, GRAIL, and Juno. His research interests include gravity science, navigation, and tracking of spacecraft. Buccino is currently the instrument operations lead for the Juno Gravity Science investigation.



**Daniel Kahan** is a senior member of the Radio Science Systems Group at NASA's Jet Propulsion Laboratory. Over the last twelve years, he has provided engineering support for the radio science community on multiple NASA missions including Mars Global Surveyor, Mars Reconnaissance Orbiter, the GRAIL lunar mission, the International Cassini mission to Saturn, Mars Science Laboratory, and Juno.



**Kamal Oudrhiri** is the manager of the Radio Science Systems Group at NASA's Jet Propulsion Laboratory and is currently the deputy project manager of the Cold Atom Laboratory. Oudrhiri has led multi-disciplinary teams through the design, implementation and delivery of flight hardware to the radio science community. Over the last decade, Oudrhiri served in key roles on multiple NASA missions.





***Oscar Yang** is a Signal Analysis Engineer in the Radio Science System group at Jet Propulsion Laboratory (JPL). He received his Ph.D. from the Aeronautics and Astronautics Engineering Department at Purdue University. His current research focuses on remote sensing of earth and planetary atmospheric and ionospheric disturbances using radio science and airglow measurements.*